Comparison of Extensive Air Shower Simulations for JEM–EUSO using CORSIKA and CONEX codes.

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1 Monte Carlo simulations of EAS development.

The goal of this work is to compare results of different method/codes for Extensive Air Shower (EAS) simulations. As the most sofisticated code we use CORSIKA [1]. CORSIKA has several options of high energy interaction model used in simulations. We examine models called QGSJET-II [7] [8], SIBYLL [10], HDPM and EPOS [9].
Hadronic interactions at energies below about 80 GeV can be simulated with two options: GHEISHA and FLUKA [5] [6]. We have used FLUKA with CORSIKA simulations.
CORSIKA has a mechanism of thinning, which is the method of replacing simulations of many subshowers/subcascades by one with the proper weight. Without this method it would be impossible to simulate showers at JEM-EUSO energies because of very long time of simulation required. However, this method is producing artificial fluctuations in EAS development. To minimalise these fluctuations we set maximum weight, and therefore force program to simulate more showers with limited weights, and smear fluctuations.

We have also used the CONEX code [2] [3] [4]. These are approximate simulations. CONEX is using GHEISHA for low energy interaction model. CONEX has a few options of high energy interaction model to be selected.

We performed all simulations for primary proton and iron nuclei and the zenith angle $\theta = 60°$.

Simulations were performed mainly on the computer cluster in Kosice, Slovakia. We used nearly the same 9 PC-like computers with Red Hat Linux. Each has 4 core processor.
Some simulations were performed on computers in Kielce, Poland.
We were unable to run CORSIKA and CONEX on computer cluster in Riken due to software reasons. We hope, that it would be finally possible, but requires some more effort.
It was possible to compare the computer performace: computers in Kosice are about two times faster, than those in Riken ('Linux cluster') in the real time.

In the table 1 we present summary of CORSIKA simulations. Different options are indicated. We evaluate the average time of simulation (one process per one processor core).

Table 1: Table of CORSIKA simulations: $\theta = 60$ deg, Fluka, THINH 0.1 10 Simulations were done on the 9 PCs of the cluster in Kosice, Slovakia, ((**) simulations on the computers in Kielce, Poland). (*) for some runs with EPOS we do not have information on individual EAS parameters (but individual longitudinal profiles).

model	$E(eV)$	THIN parameters	number of EAS	time per EAS (min)
primary protons				
QGSJET-II	10^{19}	10^{-6} 10^5 0	30	90.6
SIBYLL	10^{19}	10^{-6} 10^5 0	30	36.1
QGSJET-II	$3.14 \cdot 10^{19}$	10^{-6} 10^5 0	30	86.4
SIBYLL	$3.14 \cdot 10^{19}$	10^{-6} 10^5 0	30	66.7
HDPM	10^{20}	10^{-6} 10^5 0	100	132.1
QGSJET-II	10^{20}	10^{-6} 10^5 0	100	170.8
SIBYLL	10^{20}	10^{-6} 10^5 0	100	135.9
EPOS	10^{20}	10^{-6} 10^5 0	30	247.3
EPOS	10^{20}	10^{-6} 10^5 0	20*	247.8
EPOS	10^{20}	10^{-5} 10^6 0	20*	326.5
QGSJET-II	$3.14 \cdot 10^{20}$	10^{-6} 10^5 0	30	373.0
SIBYLL	$3.14 \cdot 10^{20}$	10^{-6} 10^5 0	30	307.9
QGSJET-II	10^{21}	10^{-5} 10^6 0	30	172.3
SIBYLL	10^{21}	10^{-6} 10^6 0	60	150.7
primary iron				
QGSJET-II	10^{19}	10^{-6} 10^5 0	30	54.3
SIBYLL	10^{19}	10^{-6} 10^5 0	30	35.9
QGSJET-II	$3.14 \cdot 10^{19}$	10^{-6} 10^5 0	30	91.2
QGSJET-II	10^{20}	10^{-6} 10^5 0	88	458.1**
SIBYLL	10^{20}	10^{-6} 10^5 0	50	131.6
SIBYLL	10^{21}	10^{-6} 10^6 0	30	150.7

2 Longitudinal distributions of 10^{20} eV proton induced EAS at zenith angle 60°.

We compare two characteristcs of simulated longitudinal distributions for EASs with the same primary particle being proton, the same pri-

Table 2: Time (in minutes) of 100 shower simulations with CONEX. $\theta = 60$ deg. Simulations were done on the 4 PCs of the cluster in Kosice, Slovakia.

log(E/eV)	19.0	19.5	20.0	20.5	21.0
model	time for 100 EAS (minutes)				
	primary protons				
QGSJET-II	24	38	63	115	275
SIBYLL	17	18	21	25	37
EPOS	45	67	111	240	713
	primary iron				
QGSJET-II	103	157	254	724	554
SIBYLL	32	39	48	60	78
EPOS	274	448	748	1280	2213

mary energy equal to 10^{20} eV, at the same zenith angle equal to 60°. For simulations with CORSIKA code we use different high energy interaction models indicated as QGSJET–II, SIBYLL, EPOS and HDPM. We draw results of simulations using CONEX code with QGSJET–II as high energy interaction model.
Here we compare average distributions of number of charged particles in EAS, and ionisation losses of particles in EAS evaluated in (GeV 5g)/cm^2, i.e. per 5 gram/cm^2 slab. (In the case of CONEX, it is not clear: it seems to be a fault in description in output from the code).

Highlighted: The ratio of number of particles in EAS to the ionisation losses is effectively constant in important depth range for JEM-EUSO as follows from the Fig. 4.

3 Energy losses in longitudinal development of proton induced EAS at zenith angle 60° and primary energy 10^{20} eV.

CORSIKA and CONEX produce in their outputs information about energy losses along EAS development.
In CORSIKA tables in DATnnnnnn.long files energy of particles crossing ground (observation) level is added to the distribution. CONEX is produsing *blabla*.data output file with information of energy deposit.

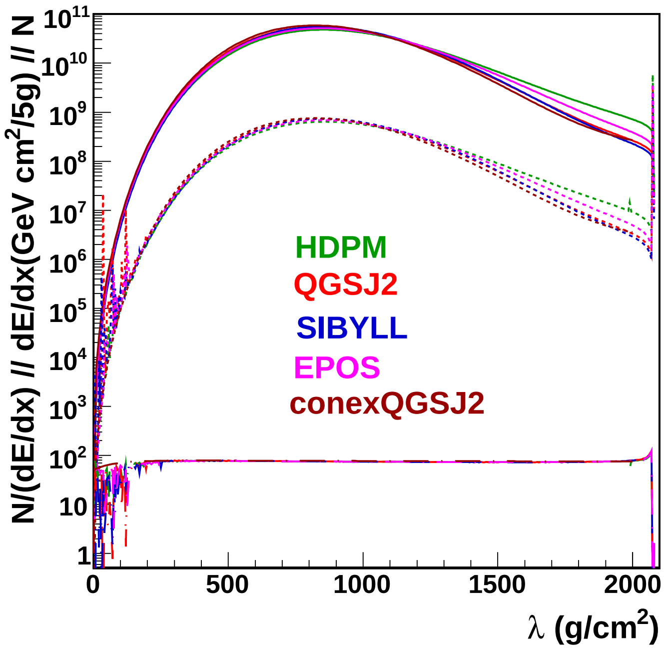

Figure 1: Longitudinal distributions of avarage number of charged particles, average ionization losses per 5 g/cm^2 slabs, and the ratio of the two distributions. Primary particle is proton with energy 10^{20} eV at zenith angle $60°$.

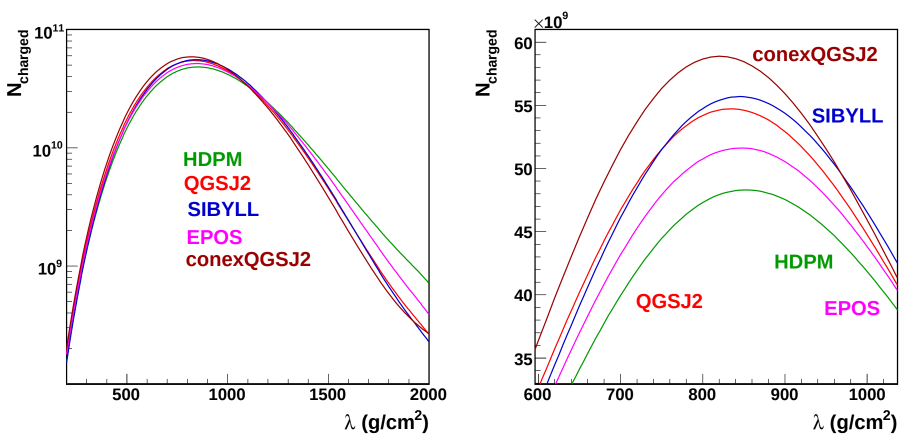

Figure 2: Longitudinal distributions of average number of charged particles. Primary particle is proton with energy 10^{20} eV at zenith angle $60°$.

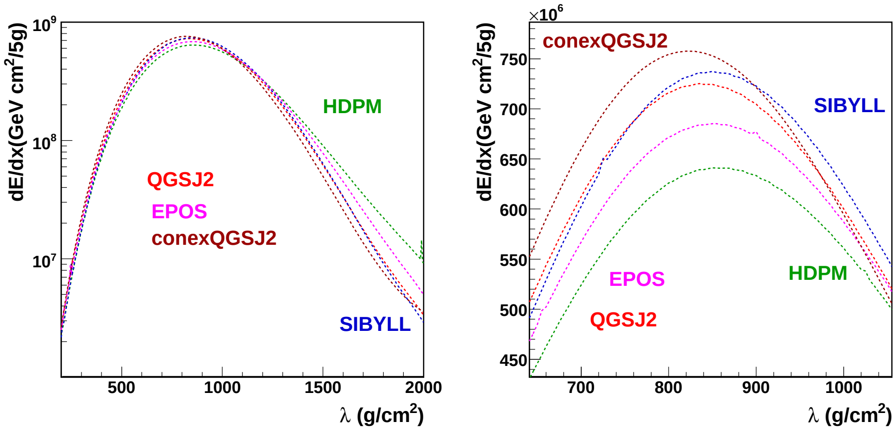

Figure 3: Longitudinal distributions of average ionisation losses per 5 g/cm^2 slabs. Primary particle is proton with energy 10^{20} eV at zenith angle 60°.

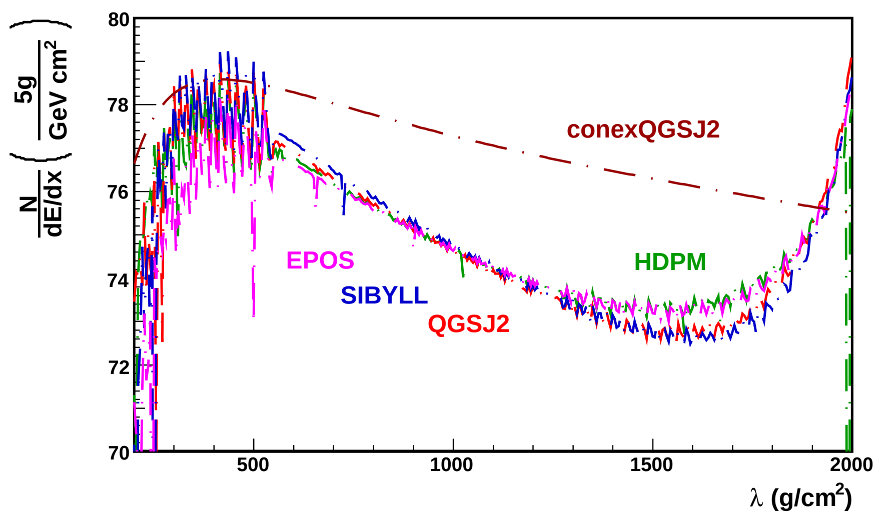

Figure 4: Longitudinal distributions of ratio of average number of charged particle (see fig. 2) and average ionisation losses per 5 g/cm^2 slabs (Fig. 3). Primary particle is proton with energy 10^{20} eV at zenith angle 60°.

Highlighted: The distributions of fractions of energy in the Fig. 5 and 6 have different width for the CONEX results from the CORSIKA results. Widths are important since the primary cosmic ray energy spectrum is steep. However, this effect is not present for the energy losses presented in Fig. 7, in CONEX case probably related to e^+e^-

losses, although taken from the column labelled as "lost".
In the CONEX case fraction of "all" (Fig. 5 and 6) is lower than fraction indicated as "lost" (Fig. 7). This is not clear.

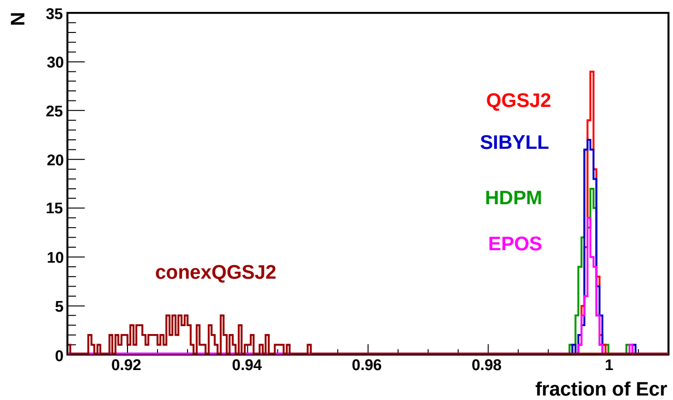

Figure 5: Fraction of primary proton energy distributions for CORSIKA and CONEX simulations for individual showers. For CORSIKA it is the sum of column "SUM" in CORSIKA DATnnnnnn.long output file. For CONEX it is the sum of column "all" in the part `"X profile for effective total energy deposit"` of *blabla*.data output file. Primary particle is proton with energy 10^{20} eV at zenith angle 60°.

4 Xmax and EAS development.

The difference between interaction models can be 'visible' in the depths of the first interaction (i.e. directly related to the cross section) and in the EAS development (i.e. cross section values and other interaction properties like elasticity, multiplicity, kind of produced particles etc.). Statistics presented in the figures 8, 9 and 10 are 100 showers for all cases, but 30 showers in the case of CORSIKA–EPOS model (see the table 1).

In the Fig. 8 distribution of the first interaction depths is shown. As the target particle atomic mass can be selected from air mass composition, the distributions can be a sum of 2–3 exponential distributions. The differences reflect the differences between cross sections in the models. The CONEX and CORSIKA distributions for QGSJET–II models are resonably the same, as they should be.

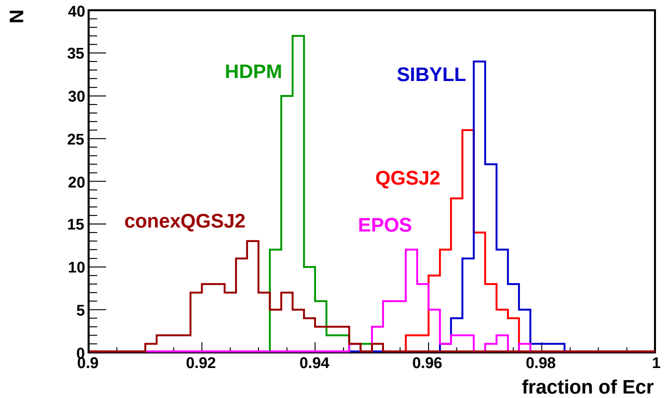

Figure 6: Fraction of primary proton energy distributions similar to presented in the Fig. 5, but the sum does not include last 4 steps near to observation level, and therefore does not include energies of particles hitting the ground. Primary particle is proton with energy 10^{20} eV at zenith angle $60°$.

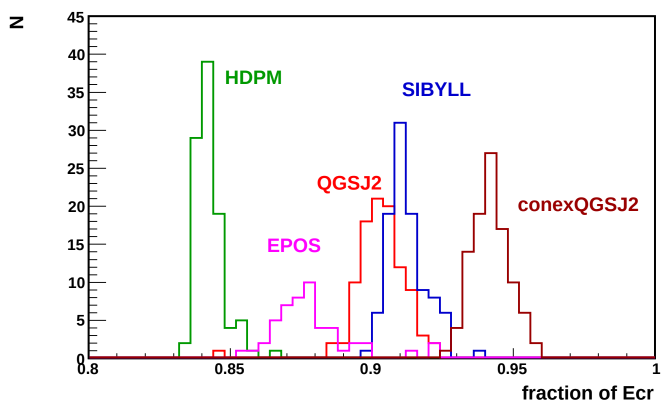

Figure 7: Distributions of the fraction of primary proton energy in charged electromagnetic component for CORSIKA and CONEX simulations for individual showers. For CORSIKA it is the sum of columns "EM IONIZ" and "EM CUT" in CORSIKA DATnnnnnn.long output file without 4 last 5 g/cm^2 steps near to the ground level. For CONEX it is the sum of column "lost" in the part `"X profile for effective total energy deposit"` of *blabla*.data output file. Primary particle is proton with energy 10^{20} eV at zenith angle $60°$.

In the Fig. 9 we presented distributions of the Xmax depths for different models. This would reflect expected Xmax for different models in observation conditions.

In the Fig. 10 we show distribution of the difference between the Xmax value and the depth of the first interaction. This reflects EAS longitudinal development in the rising part. Not only differences in cross sections, but also other parameters of high energy interaction models can be responsible for the difference between presented distributions.

In the Fig. 11 we show distribution of the number of charged particles at maximum of EAS development – $N_{ch\ max}$. This is related to observed number of photons in JEM-EUSO at the maximum of EAS signal.

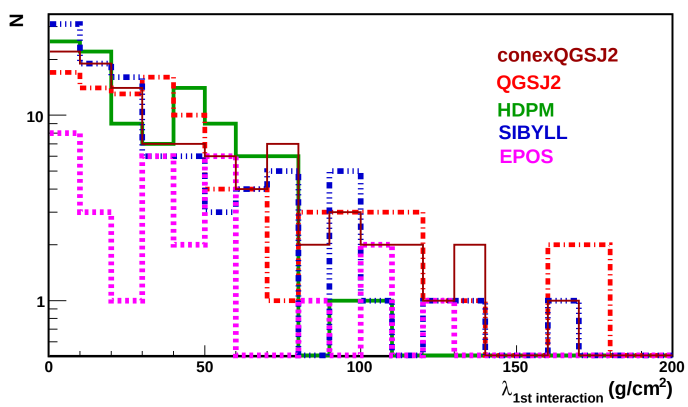

Figure 8: Distributions of the first interaction depths. Statistics is 100 showers in each case, but 30 showers for EPOS model. Primary particle is proton with energy 10^{20} eV at zenith angle 60°.

5 References

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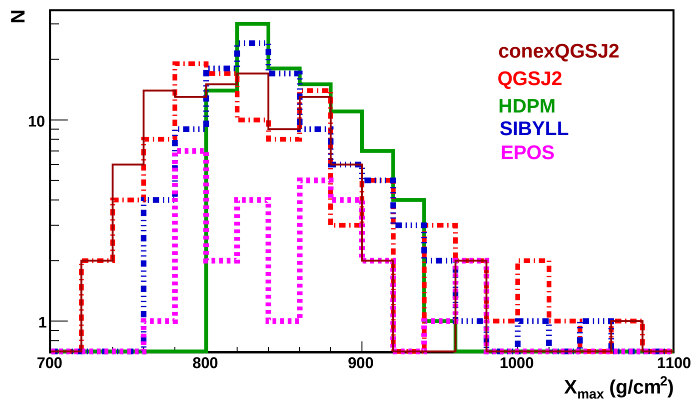

Figure 9: Distributions of Xmax for charged particles from CORSIKA/CONEX fits in their outputs. Statistics is 100 showers in each case, but 30 showers for EPOS model. Primary particle is proton with energy 10^{20} eV at zenith angle 60°.

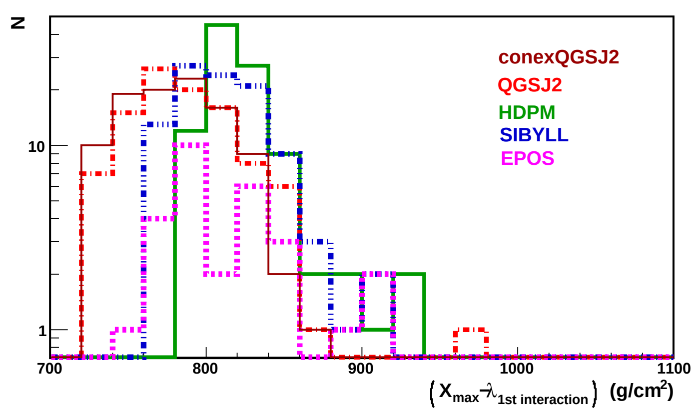

Figure 10: Distributions of the difference between Xmax for charged particles from CORSIKA/CONEX fits in their outputs (see Fig. 9) and the first interaction depths (see Fig.8). This reflects EAS development dependence on the high energy interaction model. Statistics is 100 showers in each case, but 30 showers for EPOS model. Primary particle is proton with energy 10^{20} eV at zenith angle 60°.

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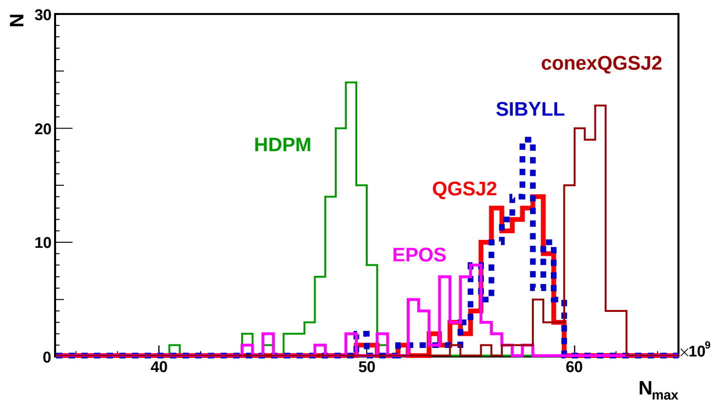

Figure 11: Distributions of Nmax for charged particles. Statistics is 100 showers in each case, but 50 showers for EPOS model. Primary particle is proton with energy 10^{20} eV at zenith angle 60°.

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